

Zero Emission Coal, A New Approach and Why It Is Needed

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Abstract

A new approach to zero emission coal-based power generation originated at Los Alamos National Laboratory is being pursued by the Zero Emission Coal Alliance (ZECA), an international coalition whose goal is **no** atmospheric emissions from coal-fueled power and hydrogen production plants. The avoidance of atmospheric emissions addresses carbon dioxide, in addition to the more commonly considered coal by-products such as NO_x, SO_x, particulates, and heavy metals. The new approach combines and updates a number of concepts previously tested separately at the pilot plant scale, but in a new, highly integrated design. The integrated approach will provide fuel to electric energy conversion efficiencies of approximately 70%, double that of today's conventional power plants, while simultaneously yielding a pure, high-pressure CO₂ stream that is ready for sequestration. For sequestration, ZECA is examining the conversion of the CO₂ into mineral carbonates, thereby achieving safe and permanent disposal of the CO₂ in an inert solid form. The high efficiency power generation step provides for a substantial reduction (~ a factor of 2) in the amount of fuel consumed per unit of power reduced, thereby reducing the amount and cost of by-product disposal by a similar factor. Unlike most other emission reduction processes being investigated, which typically offer only marginal and short-term improvements, the ZECA concept is a long-term solution capable of supplying many centuries of abundant, secure, clean, low cost, coal-based fossil energy. As the underlying chemistry of the process works on carbon, the zero emission coal (ZEC) technology is also adaptable to a wide range of other fuels including biomass, heavy oils, tars, natural gas, etc.

Introduction

Coal based power generation systems face fundamental issues, which unless resolved will become ever more acute as world energy consumption grows and as the world demands ever more environmentally friendly sources of energy. Coal is viewed, by a wide segment of the public, as a dirty fuel, responsible for emissions of sulfur, nitrogen, mercury, other heavy metals, and also ash in the form of very fine particulates. From the greenhouse gas perspective, coal is also a very carbon intensive fossil fuel, but at the same time coal has a number of fundamental advantages. It is by far the most abundant conventional fossil fuel, with sufficient resources to last for centuries even with greatly increased rates of use worldwide. It is also by far the cheapest fossil fuel. Finally, with the growing concerns over energy security, many of the countries not blessed by large oil and gas reserves instead have tremendous coal reserves. For example, Australia and the United States have sufficient coal to meet all their energy needs for centuries to come, even with substantial exports. A major fraction of the world's coal is in fact found in politically stable countries, with large amounts in developing countries such as China and Indonesia, where the coal could serve to boost their energy sources and related economies.

Fossil fuels are fully fungible with only relatively modest price increases. Coal to liquids technologies have been used for over half a century with Sasol currently being the major player. At their relatively modestly sized facilities, liquid fuels are being produced at prices comparable to \$30-\$40/ barrel of crude oil, these prices including both capital and processing costs. This price is already less than the price currently being paid by most Europeans for gasoline. With the inclusion of gains in knowledge from extensive operating experience and new technologies, coupled with an increase in plant scale, newer plants would be able to approach prices comparable to the US costs for liquid fuels.

Major demonstrations of significant cost reductions on fuel conversions have already been demonstrated on very major scales over relatively short time periods. Prices for the conversion of Canadian oil sands to synthetic crude have dropped by a factor of roughly 3 to under \$10 per barrel since the 1980s. Hydrogen plays a key role in such conversion processes as hydrogen must be added to the solid carbon found in coal in order to make liquid fuels, and to oil-based hydrocarbons in the refining process.

With the promise for coal to supply our energy needs for centuries to come, one remaining security issue must be addressed, namely environmental security. Although, major progress has already been made in cleaning emissions from coal-fired power plants, more work remains. The pending new emission regulations on mercury, particulates, NO_x and SO_x emissions, will provide even cleaner coal power; but the job will still be far from complete, even for these pollutants.

Furthermore, carbon dioxide emissions remain to be addressed. Unlike other emissions that can be considered to be only trace components of the combustion process, carbon dioxide is a

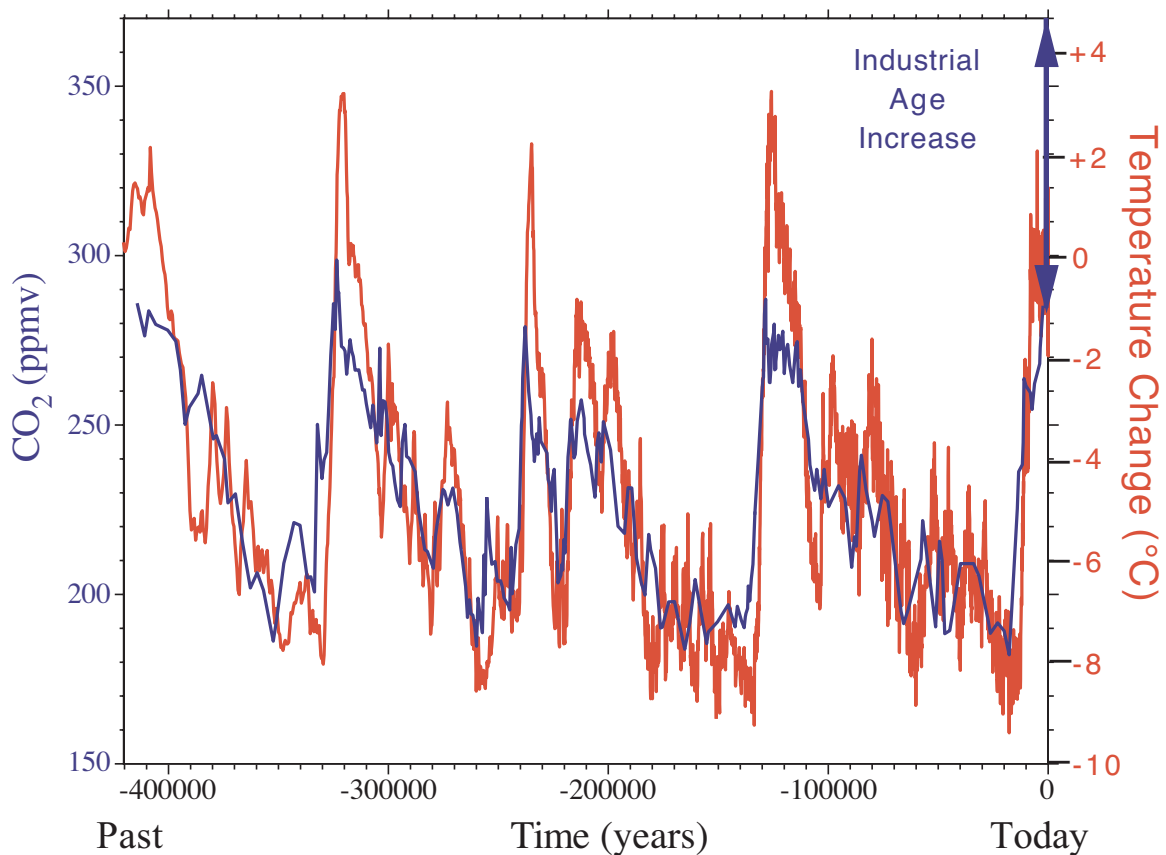


Figure 1: Ice core data relating atmospheric carbon dioxide concentrations and temperatures over the last 420,000 years. From Petit et al., *Climate and Atmospheric History of the Past 420 000 years from the Vostok Ice Core, Antarctica*, **Nature** 399.

problem of a completely different scale. More tons of CO₂ are produced by a power plant than coal fuel is input to supply it. As such, retrofit changes are not expected to be sufficient to deal with this issue^[1]. A fundamental redesign of power plants is the most likely solution. Such a redesign also provides the opportunity to simultaneously eliminate all other airborne emissions.

Carbon Dioxide Issues

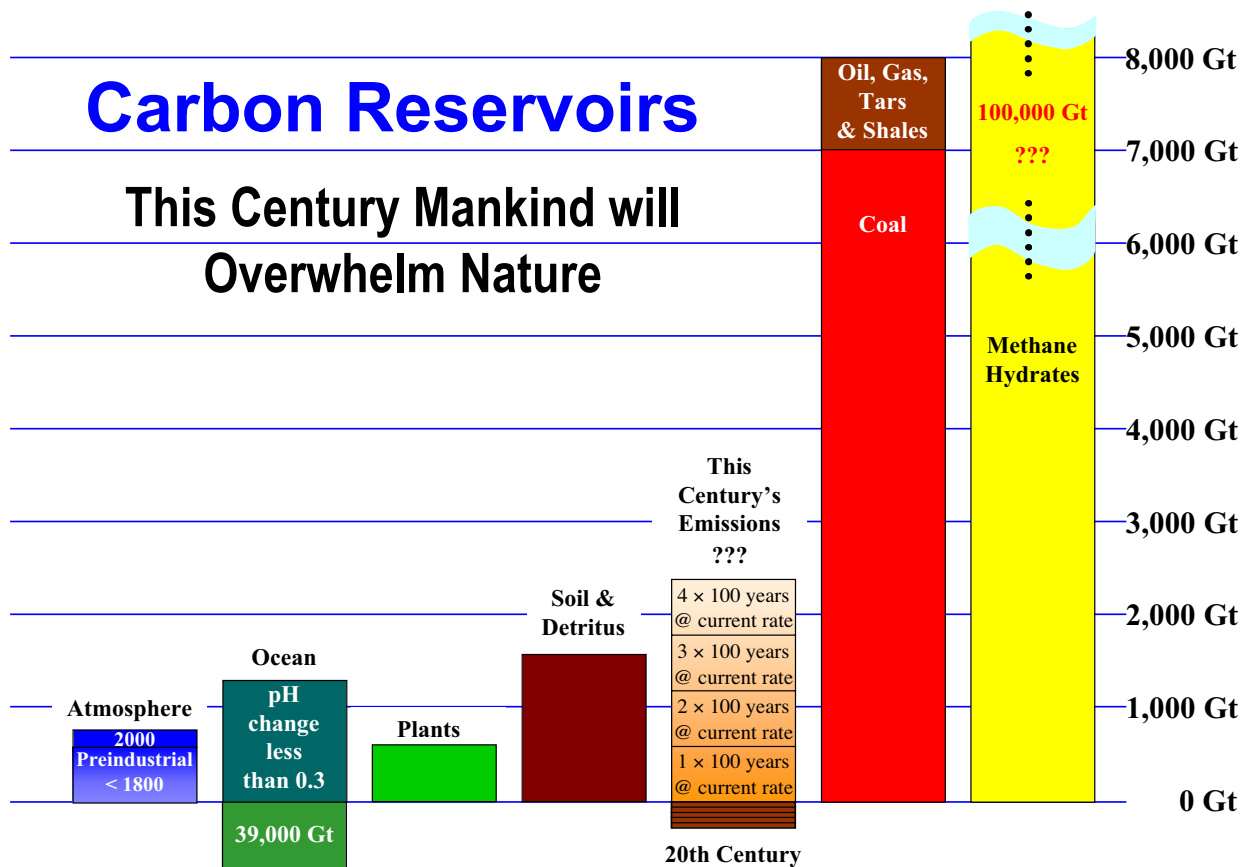
Carbon dioxide emissions are an area of growing concern worldwide. The list of potential impacts goes well beyond the currently highly publicized issue of global warming, whose validity and effects are still being debated. Carbon dioxide is a well-known greenhouse gas, yet because of the complex interactions between the different components of the ecosphere, the true impacts of increased CO₂ on global temperatures are not fully understood. This issue is further clouded by other pollution effects, such as particulates, soot, and sulfur dioxide that have their own effects on the planet radiation balance. Fig. 1 shows the clear correlation of between atmospheric CO₂ levels and global temperatures. However, it is unclear from the graph, which is the leading term. However, there is growing scientific consensus that there has been a slight increase in global temperatures since the beginning of the industrial revolution^[2]. Temperature changes have impacts on ocean temperatures and salinity which affect water densities that drive ocean circulation^[3]. Changes in ocean circulation potentially have large positive or negative feedback

on global temperatures. Other less well-known consequences of increased atmospheric concentrations of CO₂ include an acidification of the ocean and plant preferences in the biosphere.

Due to mixing and exchange of CO₂ between the atmosphere and the surface layers of the ocean, an equilibrium is established. As atmospheric concentrations of CO₂ rise, so do the concentrations of aqueous CO₂ in the ocean, which in turn result in increases of HCO₃⁻, CO₃⁼ and H⁺ ions and thus the acidity of the ocean. The result is an acidification of the ocean surface layer, a pH change of about 0.3 being caused by doubling CO₂ concentrations in the atmosphere from their preindustrial levels^[4]. Experiments at the biosphere have shown that such pH changes stunt coral growth by 30%^[5].

There are two different photosynthetic pathways that have been developed by plants, most plants incorporating the older C3 pathway and some the evolutionary newer C4 pathway. The C4 pathway is favored at higher CO₂ concentrations and higher temperatures, thus giving these plants an advantage over the C3 plants at a time of CO₂ driven global warming^[6]. This will in turn result in changes in the predominance of different plant species in the different ecosystems. The magnitude and impact of such changes are not fully known, but are likely to be non-linear: small changes having minor or virtually no known impact, and larger changes having potentially very major impacts. The transition point between these two realms is also uncertain. With such complexity and uncertainty, prudence argues for maintaining CO₂ levels near their preindustrial levels.

Since the beginning of the industrial age, atmospheric levels have increased by 31%^[7]. This rise is well correlated to anthropogenic CO₂ emissions, although only roughly half of the total emissions are reflected in atmospheric CO₂ concentration increases. The rest has been removed through natural sinks which are not well quantified. Although there is already widespread concern over the anthropogenic CO₂ emissions that have and continue to occur, the real issue is the scale of potential future emissions, especially when compared to the size of natural carbon reservoir sinks. Fig. 2 compares the size of the various carbon reservoirs, with both conventional and non-conventional fossil fuel reservoirs, such as methane hydrates, far exceeding the relatively small amounts of carbon found in the atmosphere in the form of CO₂, or found in all living plants, or organic matter in soils and other detritus. Without active intervention, the potential growth of CO₂ emissions is very large, a factor of 10 possible as illustrated in the following simple arguments. The U.S. CO₂ production and energy consumption per capita is 5 times the world average. Per capita energy consumption and per capita gross domestic product (GDP), a good measure of standard of living, are highly correlated as illustrated in Fig. 3. Thus, if current technology is used and the present world population achieves the same GDP as found in the US and other developed nations, total world energy consumption would rise by a factor of 5. When coupled with the expected roughly doubling of the world population over the next 50 years, a total growth in world energy consumption by a factor of 10 is certainly possible. It requires only a modest yearly growth of 2.3%. When this growth rate is compounded for 100 years, total energy consumption for this new century would

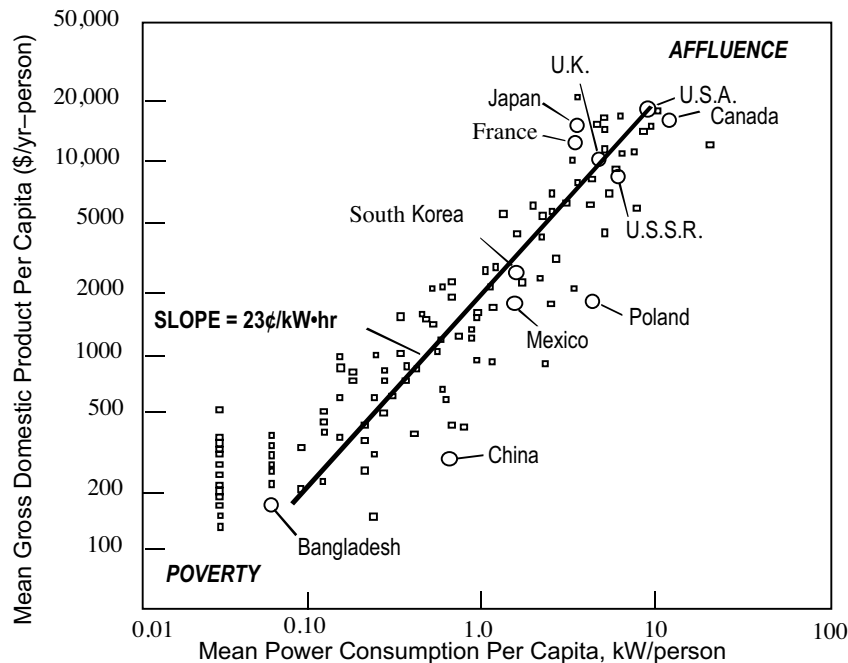


Carbon already safely stored by nature as mineral carbonates: 40,000,000 Gt

Figure 2: Potential emissions in the 21st century threaten to overwhelm nature's carbon capacity. In the above graph, the capacity of natural carbon pools is compared to potential emissions in the new century and fossil fuel reserves. On the left are the amounts of carbon currently stored in natural reservoirs. Emissions on the order of 1000 Gt of carbon are sufficient to lower the pH of the entire ocean by 0.3. At constant emissions (1 x 100 years), the new century would see 600 Gt of carbon emitted to the atmosphere. The individual blocks below the 0 Gt line in the 20th Century region represent 100 years of emissions using the 1900s emission rate. At present, energy consumption doubles every 28 years. The potential for increase is even larger. The scale set in this picture is however completely dwarfed by the amount of carbon estimated to have been already stored safely by Nature as carbonate rocks (>40,000,000 Gt).

be a factor of 4 times the present consumption multiplied by 100 years. Such a growth is clearly possible. In the just completed century, a total growth by a factor of 5 occurred over the rate at the beginning of the century multiplied by 100 years, as is shown in Fig. 2.

The above values and assumptions that led to them are clearly quite simplistic. Improvements in technology will certainly improve energy efficiency both on the energy production side and on the energy consumption side. On the other hand, new uses of energy will also evolve. For instance, today's computer related energy consumption accounts for approximately 15% of total US electric energy consumption. Also, there will clearly be a continuing push to enhance the per capita GDP in the US as time moves forward. Finally there is the assumption that the GDP in the under-developed countries throughout the world will grow significantly. This is certainly highly desirable as the alternative of keeping the majority of the world's population in poverty is an unacceptable alternative.



Fossil Energy
contributes 80% to
90% of the total World
Energy

**Cannot eliminate the
biggest resource from the
world market**

Per capita GDP versus per capita energy
consumption for members of the United
Nations. Taken from R. G. Watts,
*Engineering Response to Global Climate
Change*, Lewis Publishers, New York, 1997.

Figure 3: A graph showing the linear relationship between energy consumption and economic prosperity of nations.

To summarize, the overriding issue is not the anthropogenic CO₂ emissions to date, rather the enormous emissions possible given the huge reservoirs of fossil fuels available and their likely use given their dominance of the world energy supply, their low cost, and availability. With the potential large growth in world energy demand and the fact that just 100 years at the current rate of emissions is approximately equal to the amount of carbon currently found in the entire atmosphere and in all the world's biomass, world per capita emission rates will have to be brought to essentially zero if we hope to have an impact. A new approach is clearly needed.

New Approach Requirements

For any proposed solution to future energy systems to be successful, it will have to meet a number of requirements which include reasonable cost, ability to provide energy for an extended time interval, be environmentally acceptable with essentially zero emissions, and finally it will have to be able to meet the scale of energy needs. A number of different approaches are being pursued. Some of these are aiming only at a partial solution, either because of limited resources or because of limited capabilities or goals. A number of others rely on what are still expensive oxygen separation systems. Still others rely on innovation and/or an adoption of older concepts previously pursued for other reasons. All the solutions will require substantial investment and time before they can have a substantial impact. One area of special concern is large investments in options that provide only limited improvement over existing systems. The issue is that with large growth in world energy demand, such solutions are little more than a delaying tactic, which divert resources from long-term solutions. A balance must be maintained between the required final goal and the desired short-term improvements.

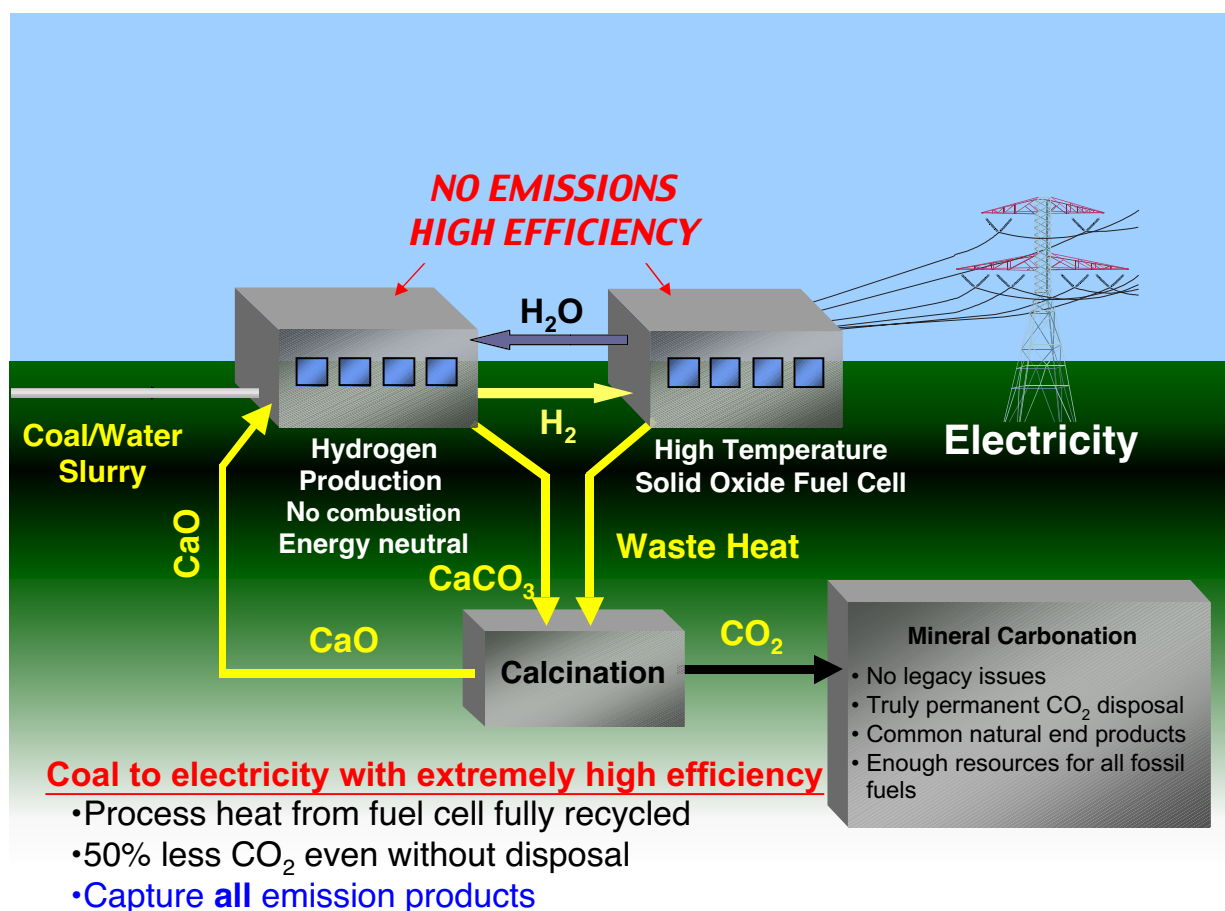


Figure 4: The new zero emission coal process originated by Los Alamos National Laboratory and being pursued by the Zero Emission Coal Alliance.

The New Approach

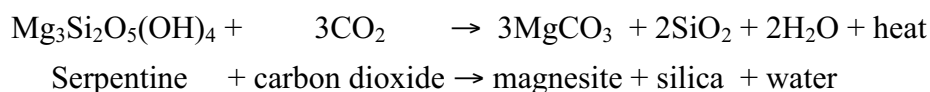
A new approach to ZEC, originated at the U. S. Department of Energy's Los Alamos National Laboratory (LANL), is being pursued by ZECA, an international coalition whose goal is **no** atmospheric emissions from coal-fueled power and hydrogen production plants. The concept has been investigated and advanced^[8] by Nexant, Inc., a Bechtel Company, which was contracted by ZECA to perform an independent evaluation of the concept. The concept, which is illustrated in Fig. 4, includes mineral carbonation as a possible route for permanently sequestering the carbon dioxide in the form of a stable mineral, magnesium carbonate. The mineral carbonation process is also being separately pursued by an independent, National Energy Technology Laboratory (NETL) funded collaboration that includes the Albany Research Center, Arizona State University, LANL, and NETL.

This paper focuses on the production of electricity from coal, although the same basic process can be used to produce hydrogen and can be fueled with any carbon-based fuel. Both the electricity/hydrogen production and the mineral sequestration portions of the ZEC technology are in early stages of development; portions of the former process have been tested in pilot plant configurations, but with different goals. Laboratory tests with the mineral carbonate

sequestration process have resulted only in data for a limited number of conditions; a number of other conditions remain to be investigated. Even with the limited effort, residence times for carbonation and other process characteristics have been significantly improved.

Mineral Carbonation

As there are several papers at this conference specifically addressing mineral carbonation, this topic will be briefly discussed. Mineral carbonation is being investigated, as it is one of the few methods for permanently sequestering carbon dioxide. The end product is an environmentally benign, thermodynamically stable, solid mineral carbonate. Mineral carbonation is the method nature has chosen to permanently sequester the carbon that once dominated the world's atmosphere and which has continued to evolve from the Earth's interior, with about 40,000,000 Gt of carbon already stored safely as carbonates^[9]. The challenge is to reduce the roughly 100,000 year time constant needed by nature to accomplish the carbonation reaction to a sub-hour time scale required for an industrial process. Due to the scale of energy production and thus the amount of carbon dioxide generated that must be sequestered, the end product will eventually be virtually worthless. Therefore, any successful implementation can have virtually no consumables other than the starting material. The starting material must be extremely plentiful and readily available at low cost. A survey of possible starting minerals has led to the choice of serpentinite as the long-term resource. This rock is abundant with sufficient rich ores available to easily handle the carbon associated with all the world's coal. The fundamental reaction one is trying to achieve is $\text{MgO} + \text{CO}_2 \rightarrow \text{MgCO}_3$. Serpentine ($\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$) is a magnesium silicate that has reacted with water and which comes in three mineral forms: lizardite, by far the most abundant, antigorite, and chrysotile, the least abundant. The serpentinite ores typically contain 35% to over 40% by weight MgO, as thus are very rich. The net mineral carbonation conversion reaction is



Although the reaction actually generates heat (~ 63 kJ/mole of CO_2 , compared with ~ 500 kJ resulting from the oxidation of enough coal to produce 1 mole of CO_2), if the reaction is carried out in a non-favorable manner one may still have to supply energy to the reaction which cannot be usefully recovered in later stages of the process.

A number of different reaction routes have been, are currently being, or will be investigated. These range from a hydrochloric acid process^[10] that was meant to demonstrate the feasibility of the concept based on the reaction time and process scale issues, but not economic issues (large required energy inputs), to direct gas solid reactions which have proven unsuccessful, molten salt processes which have had initial poisoning problems, single step aqueous processes, and multiple step aqueous processes. A major advance has been made by the Albany Research Center group, which has achieved approximately 80% carbonation in about 30 minutes^[11]. This process is

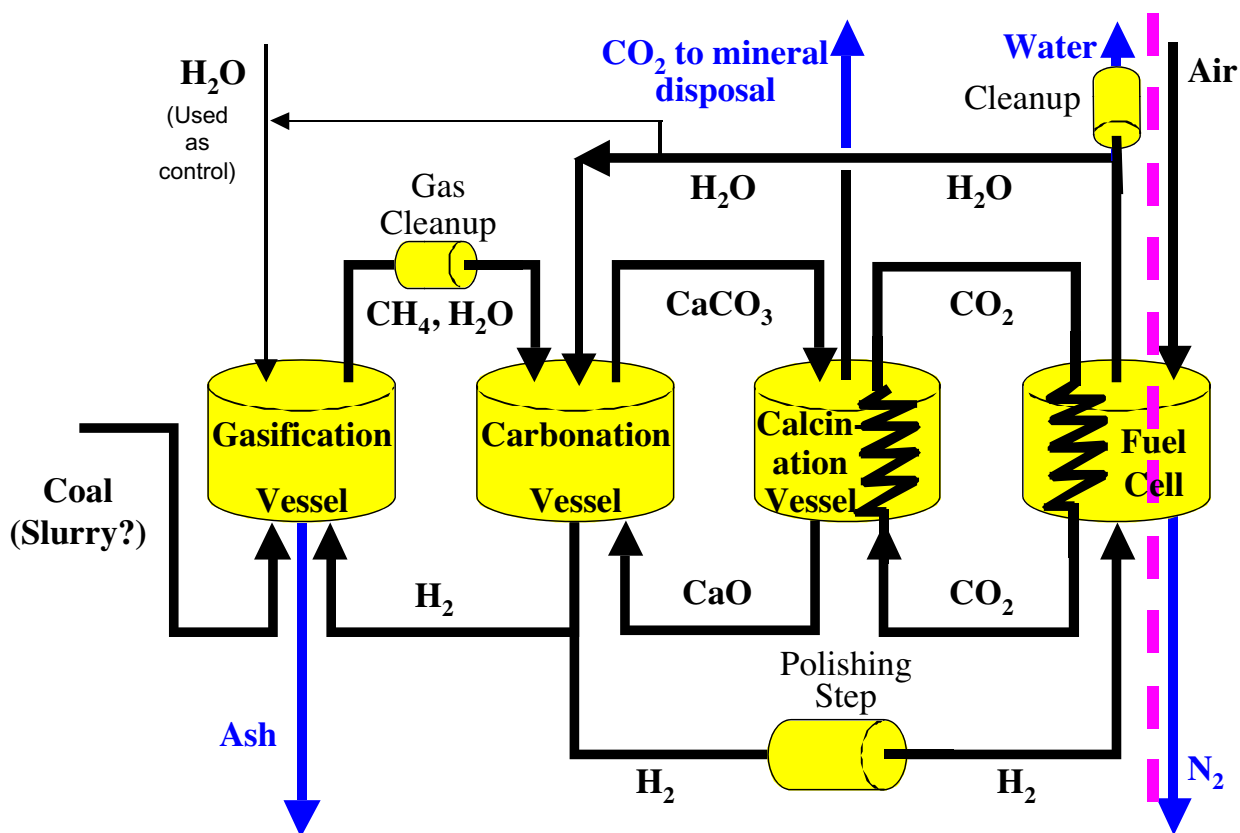


Figure 5. A schematic showing the major components of the ZECA process and their interconnections.

likely to prove economically viable when used with the fairly limited magnesium silicates (olivine) that have not undergone transformation to serpentine. It will however require further enhancements if it is to be successful with serpentine. The process currently requires a uneconomical heat pretreatment of the serpentine to drive off the chemically bound hydroxyl groups in the form of water in order to achieve the required reaction rates. In summary, substantial progress has been made, but much remains to be done. If desired goals of pressure reductions, and the avoidance of thermal pretreatment can be achieved, the study by Nexant, which includes capital and processing costs, estimates that the mineral sequestration costs will be under \$30 per ton of CO₂. This study also includes CO₂ transportation costs, as it will clearly be uneconomical to move the serpentinite ore or the end products any distance.

Gasification and Power Generation

The gasification and power production process is illustrated in Fig. 5, and described in the following paragraphs. The process includes an exothermic gasification section, a carbonation-reformer section to produce a hydrogen stream and separate out the CO₂, a fuel cell section to produce the electric power and high temperature heat, a calciner section to produce the pure stream of CO₂ and to convert the heat energy from the fuel cell into recyclable chemical energy, and a series of clean-up steps. Process temperature and pressure conditions are keys to process performance and economics, and it is strongly emphasized that process integration was and remains crucial to technical and economic feasibility.

Hydrogasification Technology

The primary purpose of the gasifier is to volatilize the carbon and to separate out the ash. The ZECA process differs from the 1970's Consol gas acceptor process^[12], which combined the gasification and carbonation-reformer step in a single process. Although that process was tested fairly successfully in a 30 ton per day pilot plant in Rapid City, South Dakota, it occasionally suffered from a failure mode in which the ash combined with calcium oxide and steam to form a cement. The Consol process also aimed at achieving only partial gasification of the coal, the residual char being burned to produce heat used elsewhere in the process. In contrast, the ZECA process isolates the ash and strives for nearly complete gasification, as it uses no combustion.

Hydrogasification was chosen as the gasification technology, as the reaction of coal with hydrogen is exothermic, thereby eliminating the need for heat inputs to this part of the overall ZEC process. The original concept from LANL did not specify a particular hydrogasification technology, so one of the first issues for the technical assessment was to find a suitable gasification technology – one that fit the overall scheme, and one where experience provided a starting point for downstream operations and overall energy and material balances. A review of the literature and discussions among Nexant's gasification specialists led to selection of the hydrogasification process developed by the Institute of Gas Technology (IGT), which is now part of the Gas Technology Institute (GTI) formed by the merger of IGT and the Gas Research Institute (GRI). IGT investigated hydrogasification^[13] in the 1970s as one of the candidate technologies for generation of methane as a synthetic pipeline gas. A 72 ton-per-day pilot plant^[14] was operated. Pilot plant reports, a demonstration plant design study and other work by Bechtel^[15] were reviewed. While the earlier hydrogasification work had different objectives, and contained a number of features not used in the ZECA project, the data and discussions with GTI personnel were very useful. GTI has since agreed to become a technical advisor to ZECA.

Hydrogasifier and Desulfurizer

The base case design investigated by Nexant uses an as-received Wyoming Powder River Basin Antelope Mine coal. The coal is ground and fed to the gasifier, the leftmost unit in Fig. 5. The gasifier is also fed a portion of the hydrogen generated in the carbonation vessel. The stream from the carbonation vessel is the source of hydrogen that reacts with the coal carbon in the gasifier to produce methane. In addition to hydrogen, the recycle stream from the carbonation vessel contains water vapor that reacts with carbon to produce CO, CO₂, and H₂. Ash from the gasifier is removed at the gasifier bottom and the gaseous product goes to the desulfurizer. Any H₂S and COS present in raw gas reacts with CaO to form CaS. By the nature of the concept for gasification and production of hydrogen that uses no combustion, other air emissions (particulates including PM 2.5, mercury, nitrogen oxides, ammonia) are avoided. Contaminants are either removed as a solid or liquid by purge streams, which are treated for proper disposal.

The major reactions in the hydrogasifier are:

$C + 2H_2 \rightarrow CH_4$ (predominant), $C + H_2O \rightarrow CO + H_2$ & $CO + H_2O \rightarrow CO_2 + H_2$ (lesser)
Pressure and temperature conditions are 815 °C and 62 bar.

Carbonation

The carbonation vessel produces hydrogen by reforming the synthesis gas and fixes the CO_2 as calcium carbonate by reaction with lime. The desulfurized gas from the hydrogasifier is sent to the carbonation vessel with steam from the solid oxide fuel cell (SOFC) and liquid water. The carbonation vessel temperature determines the ratio of liquid water and steam. In the carbonation vessel, steam reacts with methane to produce H_2 and CO_2 . Carbon dioxide further reacts with the lime (CaO) to produce calcium carbonate ($CaCO_3$). The carbonation vessel effluent is divided into two streams. The recycle H_2 stream is compressed (the compressor is not shown in Fig. 5) and fed to the gasifier. Because gasifier and the carbonation vessel operate essentially at the same pressure, minimum power is required for recycling the hydrogen stream.

In the base case investigated by Nexant there are actually two carbonation vessels. The remaining product gas from the first carbonation vessel is sent to a second carbonation vessel (not shown), which also receives liquid water and steam. The temperature of the second carbonation vessel determines the ratio between the liquid water and steam. The same reactions take place in both carbonation vessels. However, because there is a lower pressure in the second carbonation vessel and additional steam present, reaction conditions allow additional hydrogen production in this vessel. The product hydrogen from the second carbonation vessel is fed to the SOFC. The second carbonation vessel and the SOFC are essentially at the same pressure, so minimal power is required for compressing steam for the second carbonation vessel.

The two carbonation vessels reduce auxiliary power consumption. The gasifier operates best (converting a large portion of the coal to methane) at high temperature and pressure. Unfortunately, the reforming step prefers lower pressures to convert the methane to hydrogen. The recycle of hydrogen to the gasifier is a major part of the ZEC concept, and to minimize compression power requirements only the quantity of recycle hydrogen needed for gasification is compressed. The first carbonation vessel generates the recycle hydrogen, and the second vessel produces hydrogen for power production.

Calciner

The $CaCO_3$ produced in the carbonation vessels is calcined. In the Nexant base case, the calciners are fixed-bed reactors where lime is heated indirectly by a hot gas that circulates between the SOFC heat exchanger and the calciner heat exchanger. For design calculations, the heat exchange fluid is pure CO_2 at a nominal pressure of 7 bar. The hot CO_2 enters the calciner exchanger at 1130 °C and leaves at 930 °C. (The hot-gas-circulating compressor is not shown in the diagram.) The calciner temperature is maintained at 915 °C. At this temperature, $CaCO_3$ is decomposed to CaO and CO_2 , with a CO_2 pressure of about 1.3 bar. Thermal energy in the

product 1.3 bar CO₂ is used to generate steam and electricity. The product CO₂ is compressed to 1,000 psi and sent to the mineral carbonation plant. This compression is not shown in Fig. 5.

The feasibility of repeatedly recycling the lime is partly based on literature describing the Consol CO₂ Acceptor process^[16] in the 1970s. While the CO₂ Acceptor process is only indirectly applied to the present concept, some of the Consol test data were useful in preliminary assessments. The carbonation of lime with CO₂ is based on work in the mid to late 1990s. A major issue for later tests and engineering will be to determine a practical and effective way to transfer heat to the calcium carbonate and drive off the CO₂. Indirect heating with ceramic or metal alloy tubes is part of the conceptual design, but more investigation is required.

Solid Oxide Fuel Cell Power Generation

The product hydrogen from second carbonation vessel is at 815 °C whereas the fuel cell operating temperature is 1150 °C. Therefore, the gas is heated to 1,150 °C with the heat from the SOFC exhaust. Similarly, the compressed air for the SOFC, which is at 510 °C is boosted to 1150 °C by exchanging heat with the SOFC exhaust stream. (The heater exchangers for the product hydrogen and compressed air are not shown in the diagram.) The amount of air used in the SOFC is two stoics. Oxygen in the air permeates towards the fuel side of the SOFC and reacts with hydrogen. Part of the energy of the reaction directly produces electricity, and the remaining energy, which is in the form of heat, increases the temperature of the SOFC exhaust/effluent streams. The SOFC has two effluents: H₂O in the form of steam, and oxygen-depleted air. The thermal energy from both SOFC effluents is exchanged to heat the SOFC feeds and to supply the calcination heat. Most of the steam generated in the fuel cell is recycled back to the carbonation vessel. The remaining steam, which results from the hydrogen brought in as part of the coal, is condensed and subsequently cleaned. Portions of the steam and the oxygen-depleted air are sent to steam turbine and air expander units to produce additional electric power.

The ZEC concept requires a SOFC that can accept hydrogen with traces of sulfur, mercury, ammonia and other chemicals from the feedstock. Such SOFCs have not yet been designed, tested and manufactured for operation with synthesis gas. One of the crucial items on the pathway to a ZEC technology, whether that be the process described here, or others based on solid fossil feeds such as coal, petroleum coke, tar sand bitumen or coke, all need a more robust, synthesis gas capable SOFC. As everyone is aware, the vast majority of fuel cell R&D is directed in the opposite direction of what is needed by ZECA and coal-based energy in general: Government and industry R&D is working to create lower temperature SOFCs using natural gas as the main feedstock, or possibly liquid fuels reformed to suit the SOFC. While work is proceeding for hot synthesis gas cleaning systems, the Alliance members feel strongly that a significant program is also needed to research and develop a synthesis gas capable SOFC.

The ZEC technology is effectively a closed-loop process that avoids the release of gaseous effluents to the atmosphere. Thus, in addition to a more robust SOFC, the ZEC technology

requires the SOFC to avoid mixing air and the fuel. This prevents dilution of the CO₂ product stream. The ZECA fuel cell also requires a heat exchange operation internal to the SOFC. As the fuel cell provides a combustion-free path for generating the heat needed to drive the calcination reactor, which in turn recycles the CaO needed to produce the hydrogen, in a hydrogen production system an SOFC would still be desired. However, in this case the size of the fuel cell can be reduced, and its output effectively short-circuited so as to generate more heat.

POWER GENERATION PERFORMANCE

Integration of pressure, temperature and chemical reaction conditions were modeled with Aspen Plus to estimate performance. A 200 MW_e size was used for modeling based on the potential size for a hydrogasification reactor. Costs shown later are factored to a more typical coal-fired plant size of 600 MW_e, or three lines of the 200 MW_e system. Table 1 summarizes the results.

Table 1: ZEC Gasification and Power Production Performance

Power Producers	MW_e
SOFC Output	209.2
SOFC air expander	76.3
SOFC steam turbine	34.5
CO ₂ heat recovery steam generator (HRSG) turbine	9.2
Power from recoverable heat	2.0
Total power production	331.1
Power Consumers	
SOFC air compressor	97.3
Calciner CO ₂ compressor	10.6
Recycle H ₂ compressor	1.2
Steam 1 compressor	9.9
Steam 2 compressor	0.3
Non-condensables compressor	0.7
CO ₂ Compression to 69 bar	9.
Feedwater pump for CO ₂ HRSG	0.1
Lockhopper gas compressor	1.2
Total power consumption	131.1
Net power production	200.0
Performance Summary	
Coal input, kg/h	51,120
Heating value of coal, kJ/kg	20,450
Total heat input, kJ/h	1,046 × 10 ⁶
Heat rate, kJ/kWh	5,226
Efficiency, %HHV	68.9

Table 1 documents the major “producers and consumers” of power defined for the Aspen model. The amount of energy recovery and recycle within the process is reflected in the equipment cost, but it should be noted that we are not building a 330 MW plant to generate 200 MW of power. The equipment and operations are also highlighted in Table 1 as potential areas for process

improvements to reduce the need for energy recovery and recycle. While there are a number of technical uncertainties that remain to be resolved, the initial estimates of high efficiency are promising, especially when compared to other options for power generation with the separation of CO₂ and pressurization for transport and/or disposal of CO₂. The nearly 70% efficiency value in Table 1 already includes the penalties for CO₂ separation and pressurization to about 70 bar.

Improvements to the baseline process that are likely to boost overall efficiency have been identified and are being investigated. Other feedstocks –bituminous coal and lignite, coke and bitumen from tar sand processing, were also examined. Efficiency varied slightly with feed properties; and the largest variable was the feedstock tonnage, which was dependent on heating value for a fixed power output.

COST ESTIMATES

Cost estimates for a 600 MW_e net gasification and power production plant were prepared by sizing major equipment and estimating their costs. Costs for installation, construction materials and other items constituting a total plant cost were estimated from published data, experience with similar plants and other design studies. Costs for the fuel cells assume a mature technology and a price determined in discussion with Siemens-Westinghouse. The SOFC estimate does not reflect design and manufacturing changes that will be needed to make today's SOFC design more capable of operating with synthesis gas. At present it is not known if these changes will reduce or increase the estimated cost. It is clear from Table 2 that the SOFC and associated air compression equipment are the major cost component in the estimate.

Neither the cost nor performance of the process have been optimized, and there appear to be areas for improvements, as well as areas where better definition and engineering can reduce uncertainties of performance and cost.

Table 2: 600 MW_e ZEC Technology Power Plant

Cost Item	Cost, \$1,000s	\$/kW
Gasification, Vessels	145,200	242
Gasification, Rotating Equipment	66,000	110
Power Generation Equipment	535,900	893
Product CO ₂ Heat Recovery Equipment	42,100	70
Coal Feed Lockhopper Equipment	10,600	18
Ash Discharge Lockhopper Equipment	700	1
Cooling Tower Equipment	16,700	28
Balance of Plant	93,900	156
Total Plant Cost[†]	911,100	1,518

[†]Does not include process and project contingencies.

POWER GENERATION ECONOMIC COMPARISON

Two recent articles and Nexant/Bechtel experience were used to compare the ZEC gasification and power generation technology with potential alternatives. The first paper, reference A, is titled: EVALUATION OF INNOVATIVE FOSSIL CYCLES INCORPORATING CO₂ REMOVAL^[17].

Table 3 summarizes data from the paper. The cost of electricity calculations are based on 65 % operating capacity, and 20 year term of investment.

Table 3: Reference A Comparison Data

Reference A Data	Case 1A	Case 1B	Case 3A	Case 7A	Case 7B
Efficiency, HHV %	39.2	43.3	37.0	28.9	31.0
Total Plant Cost, \$/kW	1,010	943	1,642	1,981	1,943
Total Capital Cost, \$/kW	1,099	1,026	1,844	2,219	2,175
Production Cost, cents/kWh	3.13	2.92	2.10	3.18	2.97
Cost of Electricity, cents/kWh	5.79	5.41	6.57	8.56	8.24
Incremental Cost of Electricity, cents/kWh; calculated in Reference A as the difference in Cost of Electricity between plants with, and without removal.	2.37	2.06	1.33	3.41	3.14
CO ₂ Removal Cost, \$/ton; calculated in Reference A as the difference between plants with, and without removal.	51.63	49.43	15.87	28.90	31.00

Case 1A: F class natural gas combined cycle with CO₂ removal.

Case 1B: H class natural gas combined cycle with CO₂ removal.

Case 3A: Integrated gasification combined cycle, H class turbine with CO₂ removal.

Case 7A: Conventional supercritical pulverized coal with CO₂ removal.

Case 7B: Ultra supercritical pulverized coal with CO₂ removal.

The second published reference, B, is THE COST OF CARBON CAPTURE^[18]. Data from that paper are shown in Table 4. The cost of electricity is based on a 75% operating capacity and 15% capital charge rate. All the data in this reference were stated in units per kWh, so some absolute values needed for the later comparison had to be estimated by judgments.

Note that the CO₂ removal costs are calculated from the amounts of CO₂ removed and the differences between cost of electricity of plants with, and those without CO₂ removal. The ZEC technology's gasification and electric power production does not have an alternative design where CO₂ is not removed: The ZEC technology removes CO₂ as part of the concept. Thus the comparison with costs provided in the literature for CO₂ removal has to be adjusted so that the comparison is made on the basis of the cost of electricity. Natural gas prices were not provided in either paper, but from discussions with EPRI, the cost in reference A was \$2.70 per million Btu for gas and \$1.24 for coal. The references use a 90% CO₂ capture factor in their work. Obviously, higher natural gas prices will have a strong impact on the gas turbine combined cycle (GTCC) plants. The ZECA case includes a significant annual cost for reforming catalyst, and

the periodic replacement of SOFC equipment (a 5 year economic life is used for the fuel cell modules).

Table 4: Reference B Comparison Data

Reference B Data	IGCC 2000	IGCC 2012	PC 2000	PC 2012	NGCC 2000	NGCC 2012
Efficiency, LHV %	36.1	43.5	30.9	36.1	47.8	54.1
Efficiency, HHV % (estimated)	32.5	39.2	27.9	32.5	43.2	48.8
Capital Cost, \$/kW	1,909	1,459	2,090	1,718	1,013	894
Cost of Electricity; Capital, cents/kWh	4.36	3.33	4.77	3.92	2.31	2.04
Cost of Electricity; Fuel, cents/kWh	1.17	0.97	1.37	1.17	2.09	1.85
Cost of Electricity; O&M, cents/kWh	1.16	0.84	1.57	1.16	0.51	0.44
Total Cost of Electricity; cents/kWh	6.69	5.14	7.71	6.26	4.91	4.33
CO ₂ Removal Cost, \$/ton (calculated)	23.27	16.00	44.13	29.05	44.90	37.27
Incremental Cost of Electricity, cents/kWh	1.70	1.04	3.32	2.16	1.61	1.23

1. IGCC 2000 and IGCC 2012 represent integrated gasification combined cycle plants with CO₂ removal, adjusted for estimated improvements in the time from 2000 to 2012.
2. PC 2000 and PC 2012 are similar pulverized coal-fired plants with CO₂ removal.
3. NGCC 2000 and NGCC 2012 are similar natural gas combined cycle (NGCC) plants with CO₂ removal.

Table 5 shows a comparison using total plant costs and efficiencies. Availability was adjusted for all cases to 90% of capacity, and for financial factors of 12 percent cost of money and a 20-year investment term. These were applied to the cost data in Tables 3 and 4, but without process and project contingencies that are typically accounted for in the total plant cost.

Table 5: Comparison of Technologies with CO₂ Removal

Items	ZEC Case 600 MW _e	Reference A, EPRI ⁱ				
		Case 1A, F Class GTCC	Case 1B, H Class GTCC	Case 3A, IGCC with H Class GT	Case 7A, Supercritical Pulv. Coal	Case 7B, Ultra Supercritical Pulv. Coal
Efficiency, HHV %	68.9	39.2	43.3	37.0	28.9	31.0
Tons per Year per MW _e	4,090	3,630	3,280	6,620	8,510	7,920
CO ₂ Sequestered						
Total Plant Cost, \$/kW	1,520	860	790	1,400	1,710	1,680
Cost of Electricity, \$/kWh	0.0432	0.0459	0.0425	0.0447	0.0608	0.0582
	Reference B, MIT ⁱⁱ					
	IGCC 2000	IGCC 2012	PC 2000	PC 2012	NGCC 2000	NGCC 2012
Efficiency, HHV %	32.5	39.2	27.9	32.5	43.2	48.8
Tons per Year per MW _e	5,760	5,120	5,930	5,860	2,830	2,600
CO ₂ Sequestered						
Capital Cost, \$/kW	1,909	1,459	2,090	1,718	1,013	894
Cost of Electricity: \$/kWh	0.0557	0.0429	0.0649	0.0525	0.0432	0.0381

ⁱ Total Plant Costs less costs for process and project contingencies.

ⁱⁱ Likely Capital Costs with contingencies and owners' costs included.

Reference A data were more clearly defined. For example, the reference B costs are titled capital costs, but the items included in the cost are not defined. Also, the distinctions between year 2000 and 2012 plants were not clear in the publication. The comparison with reference A is based on

total plant cost, less contingency factors. The issue of how one assigns contingency costs for advanced technologies with widely different maturities introduces some inconsistency to the comparison. The ZEC technology is at the earliest stage of development with limited engineering data. However, based on the potential efficiency and costs, its viability seems sufficient for further evaluations to be worthwhile. The comparison is intended to be as consistent across the technologies as the data allow and the real value of the comparison is in the relationships, not the absolute conceptual cost numbers, which may vary over a relatively wide range.

While, as noted, it is not possible to compare costs per ton of CO₂ as traditionally done for plants with and without CO₂ separation (i.e. avoided costs), it is informative to examine the cost of electricity for systems that include the power generation and CO₂ separation with sequestration. In this comparison, the efficiency of the generation plants can be accounted for because the more efficient plants will produce less CO₂ that has to be sequestered. The sequestration method is not specified, but costs are estimated to range from \$10 to \$30 per ton of CO₂. Fig. 6 shows the results for the ZEC technology and those from reference A. Reference B is not shown to avoid clutter. Due to its high efficiency and lower fuel use, the ZEC technology with sequestration ranks with the cases 1A and 1B, which have lower costs of electricity systems and which are natural gas combined cycle operations.

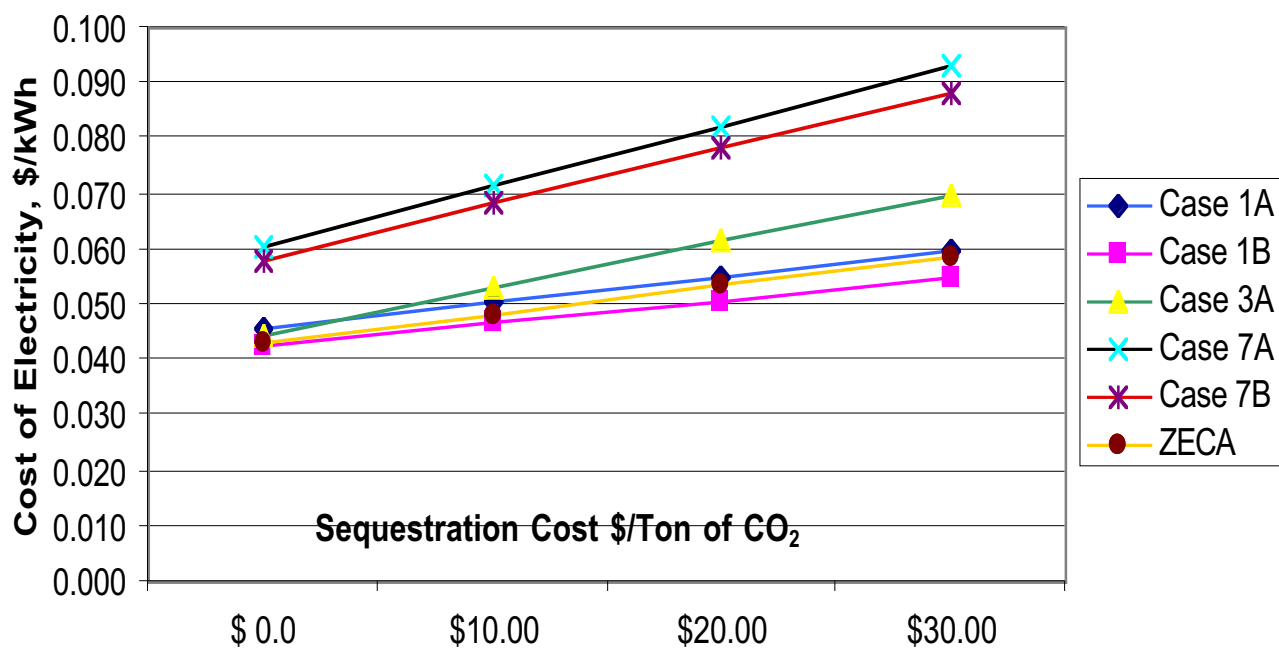


Fig. 6: Cost of Electricity for Systems with CO₂ Sequestration

Conclusion

Clean, secure power for the US and world will involve a very large effort that will require a substantial lead-time, a diverse effort, and a major investment. However, the required

investment is comparable, if not smaller than the money that will be lost through an insecure or inadequate energy supply as demonstrated by the recent energy crisis in California. The costs of retrofits to existing plants to deal with the pending new regulations of particulates and mercury emissions will raise the cost of existing coal plants to values likely to be comparable to that of a ZEC power plant. The retrofits however will not deal with CO₂ emissions that are likely to be regulated in the U.S. as they already are in some parts of the world, nor will they be able to meet the even tighter conventional emission restrictions that will surely come. Based on the ever-growing world demand for clean energy, it is likely that essentially zero emissions will be required for future power plants.

While a number of areas of technical and economic uncertainty remain, and significant work is still needed to test the feasibility of the ZEC power generation concept, the initial results show a potential for high busbar efficiency and competitive costs. Comparing the ZEC concept to other power generation systems with CO₂ capture and sequestration indicates that the ZEC concept has the potential to be less costly than other coal-based technologies, and to be competitive with natural gas combined cycle plants, even at relatively conservative fuel prices. The comparison must be tempered by the very early stage of process development for the ZEC technology. There is high potential for the process, but there are also a number of issues that require resolution before the concept can become a practical option in the mix of power generation technologies.

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